TFAWS Active Thermal Paper Session

System trade-off analysis of two-phase mechanically pumped fluid loop for thermal control of future deep space missions

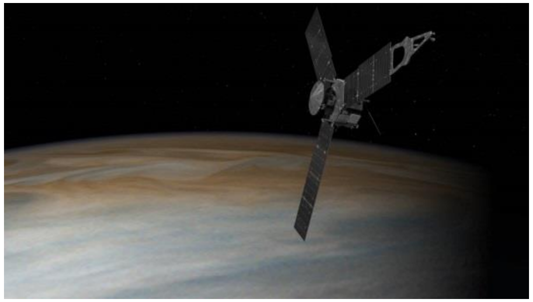
Kenichi Sakamoto
Takurou Daimaru
Hiroki Nagai
(Tohoku University)

Presented By
Kenichi Sakamoto

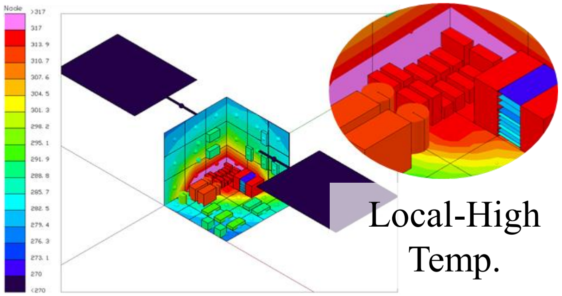
Thermal & Fluids Analysis Workshop
TFAWS 2016
August 1-5, 2016
NASA Ames Research Center
Mountain View, CA

Future deep space missions

- Exploring to the outer space
  - Extreme environment
  - Low solar power
- Requirements for thermal control system
  - Low power consumption & waste heat reclamation
  - Light weight system
  - Keeping science instruments isothermal
- Current thermal control technology
  - Loop Heat Pipe
    - Flight system integration and distance issues, Evaporator shape
  - Single-Phase Mechanically Pumped Fluid Loop
    - Large ΔT in cold plate and across loop, large mass
- Two-Phase Mechanically Pumped Fluid Loop
  - Potential ability to meet requirements



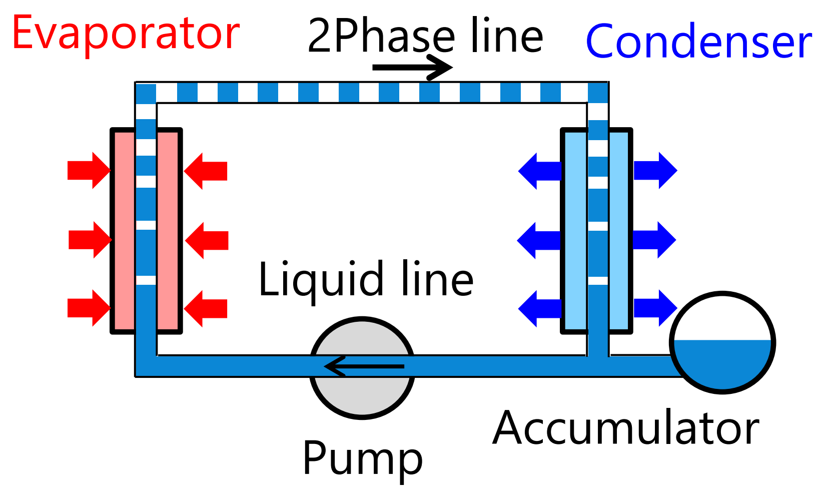
Juno
(C) NASA



Heat Dissipation

Two-Phase Mechanically Pumped Fluid Loop

- Working Principle
  - Fluid driven by pump
  - Liquid absorbs heat in evaporator and changes to two-phase flow
  - Two-phase flow dissipates heat in condenser and changes to liquid
  - Accumulator controls temperature



- Merits
  - Pump driving
    - Long heat transport distance
    - Robust start-up
  - Phase change
    - Light weight
    - Low power consumption
    - Small ΔT on the evaporator

	LHP	SPMPFL	**2PMPFL**
Distance	×	○	○
Robustness	△	○	○
Isothermality	△	×	○
Low mass	○	×	○

Researches

- Experiment project at JEM in ISS
  - To clarify effects on heat transfer and critical heat flux in flow boiling
- AMS-2
  - The first full-size 2PMPFL in space
  - Searching for dark matter at ISS
  - The working fluid is CO_2
- Working fluid selection
  - A lot of criteria
    - Heat transport performance
    - Mass of system
    - Power consumption of pump
    - Others…
- Problem
  - Considering whether the working fluids satisfy the requirements of system

AMS-2 on ISS
(C) NASA

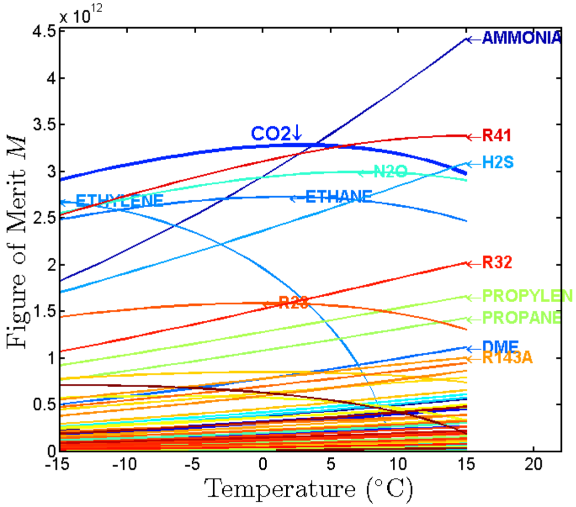


Figure of Merit of low pressure drop
H.J. Gerner et al,
ICES-2014-136, 2014

Evaluating the working fluids by total mass of system with 1D steady model of Two-Phase Mechanically Pumped Fluid Loop

- Contents
  - Evaluating method
  - Mathematical model of 2PMPFL
  - System analysis
  - Evaluating the working fluid

Evaluating method

- Requirements
  - Heat input 500W
  - Payload bench $0.5m^2$
  - Spatial uniformity on evaporator $< 3^oC$
- Constraint
  - Mass without evaporator and radiator <10kg

    *Evaporator and radiator are made with structure panel of spacecraft
- Objective function
  - Mass of system

$$M_{system} = F(\lambda, \rho, \mu, c_p, k, T, P, \sigma)$$

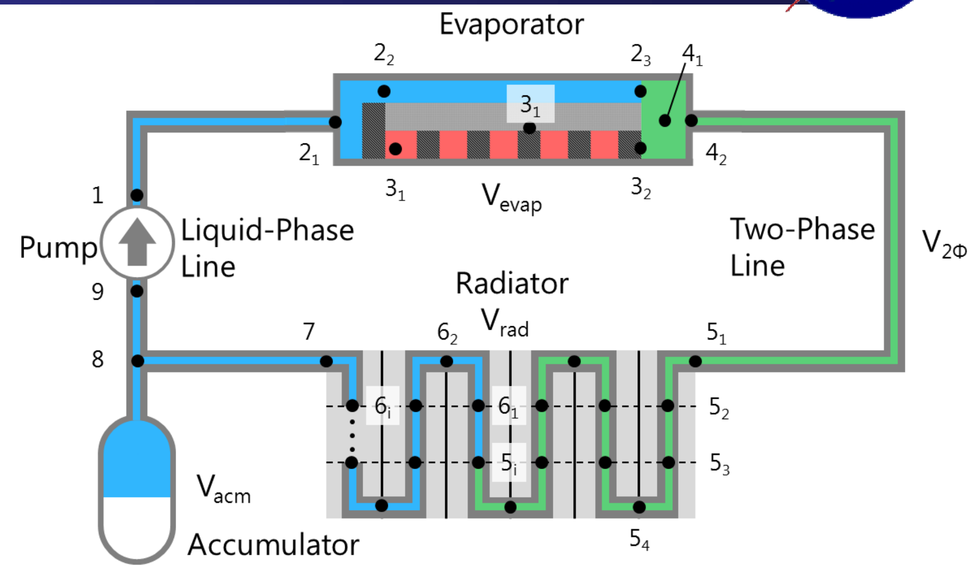
$$M_{system} = M_{pump} + M_{accumulator} + M_{fluid} + M_{tube}$$

M	Mass
λ	Latent heat
ρ	Density
μ	Viscosity
c_p	Specific heat
k	Thermal conductivity
T	Temperature
P	Pressure
σ	Surface tension

Mathematical model of 2PMPFL

Model of 2PMPFL

- Assumptions
  - Not considering conduction of tube wall
  - Not considering degree of super heat for boiling
  - Constant heat flux in evaporator



- Modeling

1 Input assumed pressure and temperature

2-4 Liquid evaporates in the evaporator

5 Two-phase flows into radiator

5-7 Two-phase is cooled by radiator

8 Accumulator controls the temperature

9 Pump provides the driving pressure

1 New initial value

Equations

- Single-phase
  - Pressure : $P_{SP}{}^{i} = P_{SP}{}^{i-1} - \frac{f_{SP} L \rho_{SP} u_{SP}{}^{2}}{2D_h}$
  - Temperature : $T_{SP}{}^{i} = T_{SP}{}^{i-1} + \frac{Q_{in}}{\dot{m} C_{p,SP}}$
- Two-phase
  - Pressure :

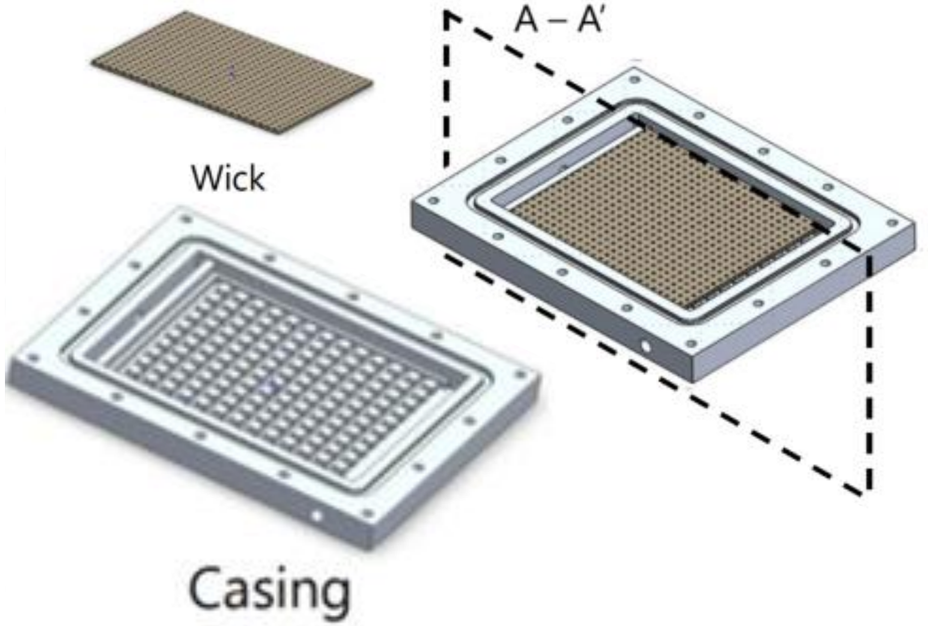
$$P_{2P}{}^{i} = P_{2P}{}^{i-1} - \left\{ \left(1 + x\frac{\rho_l - \rho_g}{\rho_g}\right)\left(1 + x\frac{\mu_l - \mu_v}{\mu_v}\right)^{-0.25} \right\} \frac{f_l L \rho_l u_l{}^{2}}{2D_{in}}$$

  - Temperature : $T_{2P}{}^{i} = T_{sat}\left(P_{2P}{}^{i}\right)$
  - Quality : $x = \frac{\left\{H^{i-1} + \frac{Q_{in}}{\dot{m}} - H_{sat,l}\right\}}{\lambda}$

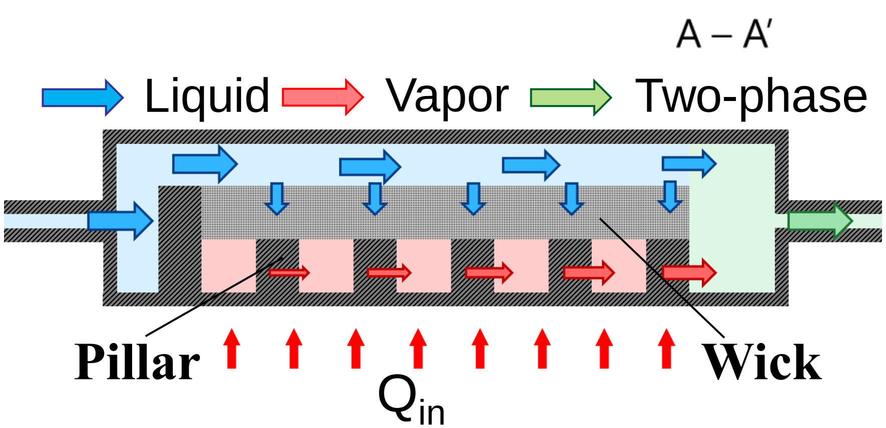
P	pressure [Pa]
T	temperature[^{o}C]
x	quality [-]
f	friction factor [-]
L	length [m]
ρ	Density [kg/m^3]
u	velocity [m/s]
D_h	Hydraulic diameter [m]
Q_{in}	heat in each cell [W]
$\dot{m}$	mass flow rate [kg/s]
C_p	specific heat [J/kg/K]
M	viscosity[Pa-s]
H	enthalpy [J/kg]
λ	latent heat [J/kg]
SP	single-phase
2P	two-phase
l	liquid
v	vapor
sat	saturation
i	position of node

Evaporator Design

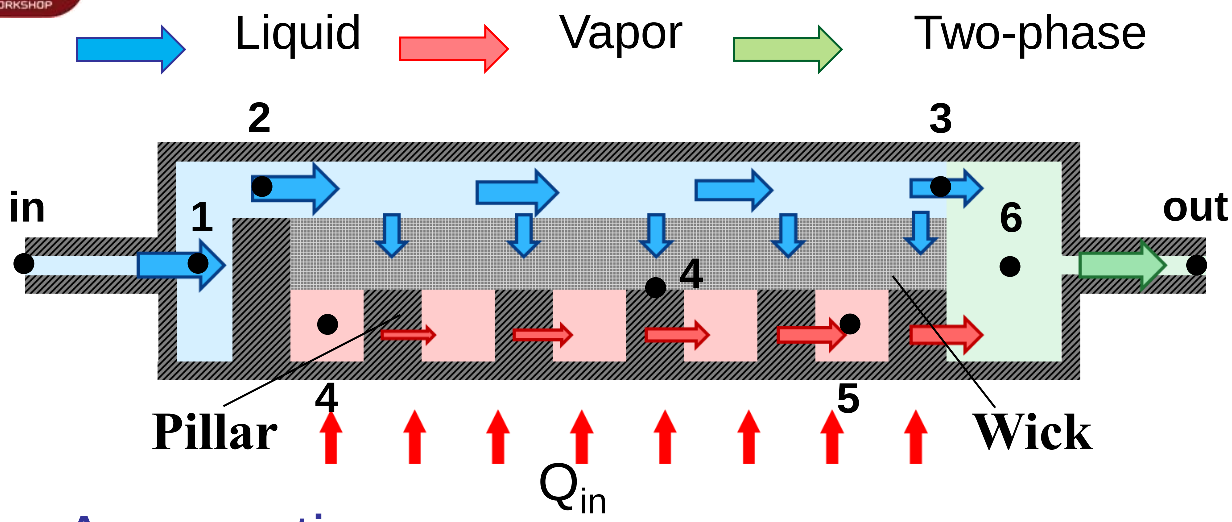
- Requirements
  - Large flat area for flexible heat load placement
  - Dimensionally and temporally isothermal benches for science instruments
- Design
  - Wick structure for uniformly supplying the liquid
  - Heat is transferred through the pillars
  - Liquid evaporates at the whole area
  - Subcooled liquid is heated in wick and liquid chamber

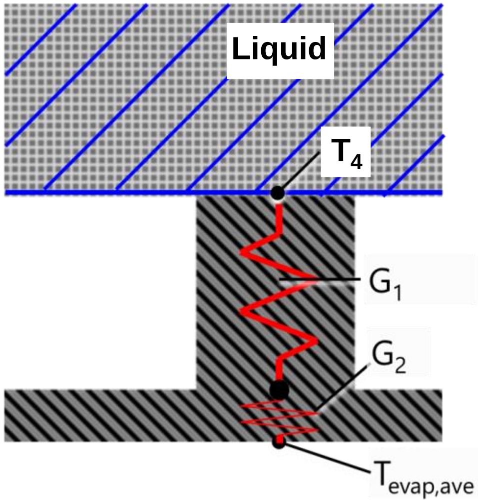


Evaporator design
Eric Sunada et al, ICES-2016-129, 2016



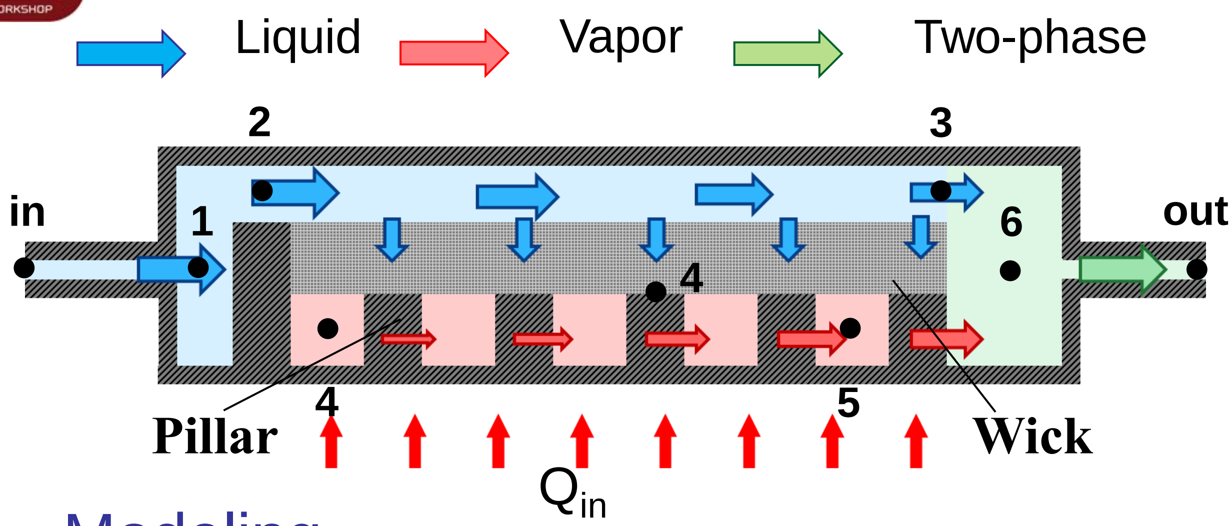
Evaporator model

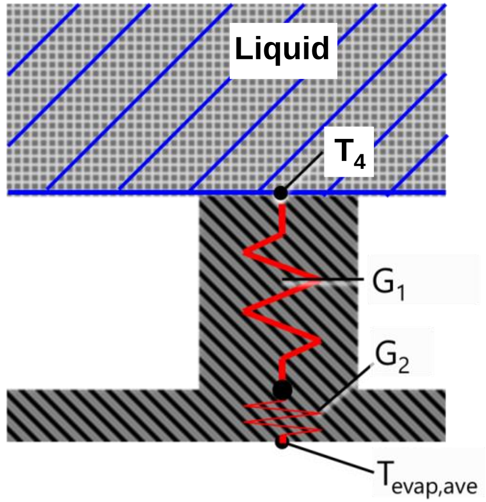




- Assumption
  - All heat input is consumed for temperature rise and evaporation of fluid
  - All heat is transferred through the pillars
  - Liquid flows uniformly through the wick
  - Retreat of the meniscus in the wick is neglected
  - Pressure at the vapor-liquid junction is equal to pressure of the liquid

Evaporator model



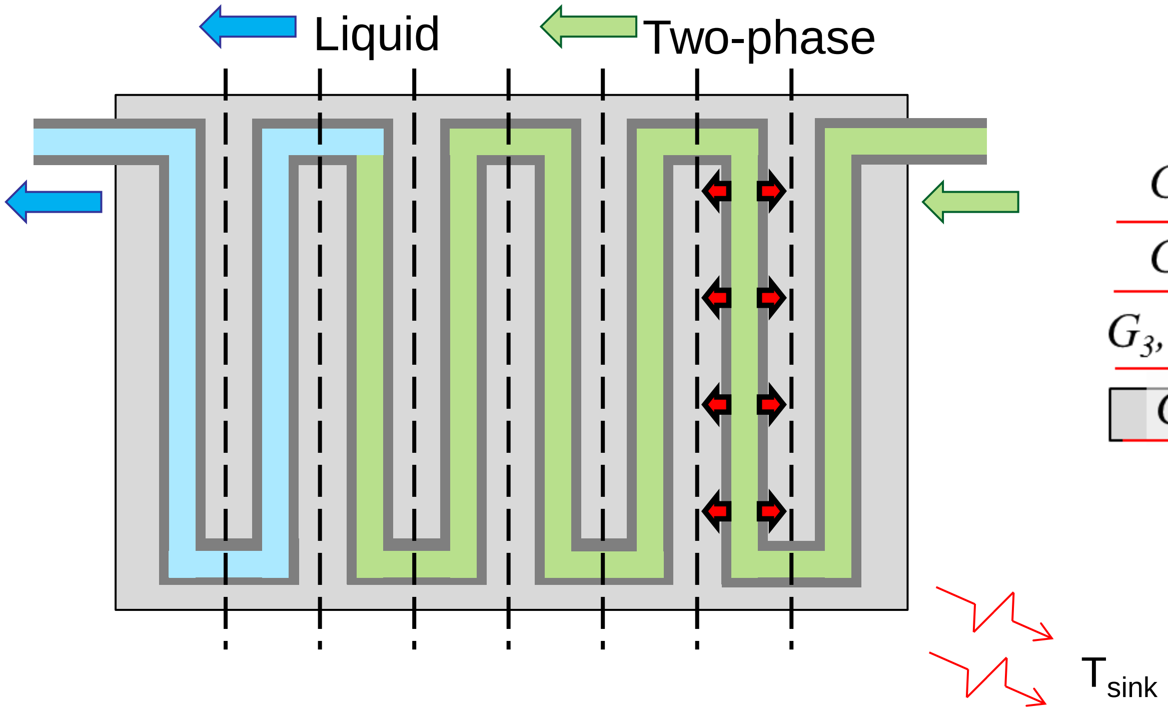


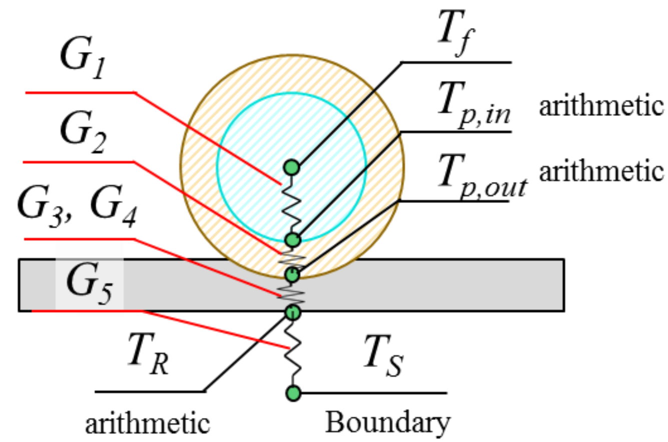
- Modeling
  - 1 Liquid flows into evaporator
  - 2-3 Some liquid flows top of evaporator

    Temperature of liquid rises by heat leak $T_3 = T_2 + \frac{Q_{HL}}{\dot{m}_l c_p}$
  - 4 The wick absorbs the rest of liquid $P_4 = \frac{(P_2+P_3)}{2} + \frac{2\sigma\cos\theta}{r_{pore}} - \Delta P_{wick}$

    Heat input evaporates liquid at the surface of wick
  - 4-5 Vapor flows bottom of wick
  - 6 Liquid and vapor are mixed $T_6 = T_3$, $P_6 = P_3$

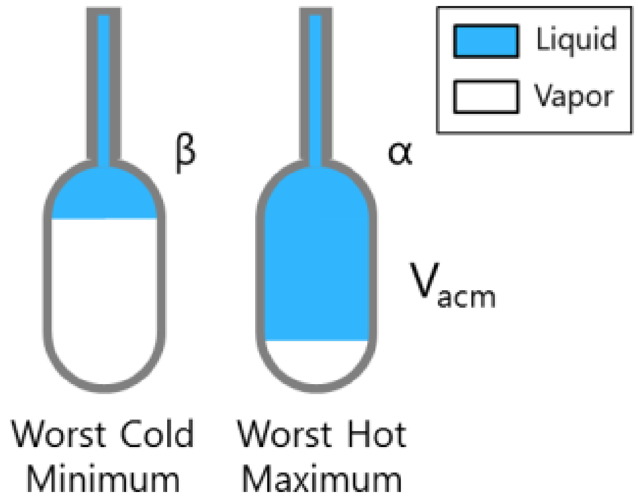
Radiator model





- Modeling
  - Tube-on-plate radiator
  - One side radiating to the cold space
  - Area is enlarged to fulfill the Net Positive Suction Head (NPSH) requirement

Accumulator model



- Modeling
  - Accumulator size is driven by these two cases
    - Startup = Liquid occupies the entire loop with some reserve fluid in accumulator (β)
    - Worst hot case = Vapor volume is maximized with some reserve vapor space in accumulator (α)

→Calculating the accumulator volume

$$V_{acc} = \frac{V_{2\phi} + V_{evap,vapor} + V_{rad}}{\alpha - \beta}$$

Mass calculation

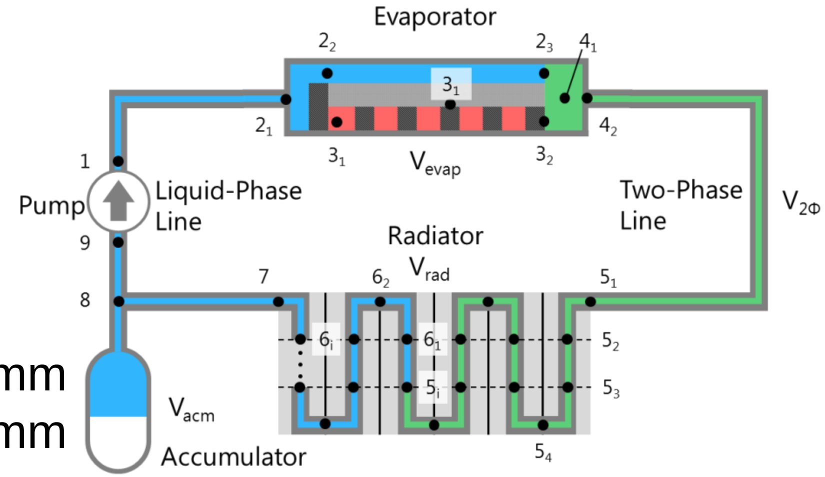
- Pump
  - $M_{pump} = 0.25W_{pump}$ (Power : $W_{pump} = \Delta P\dot{m}/\rho_l\eta_{pump}$)
- Accumulator
  - $M_{acc} = \rho_{acc}\pi\delta_{acc}D_{acc}L_{acc}$ (Thickness : $\delta = \frac{PD_{out}}{2(S+0.4P)}$)
- Fluid
  - $M_{fluid} = \rho_l(0.15V_{acc} + V_{tube-in} + V_{evaporator})$
- Tubing
  - $M_{tube} = \rho_{tube}V_{tube}$

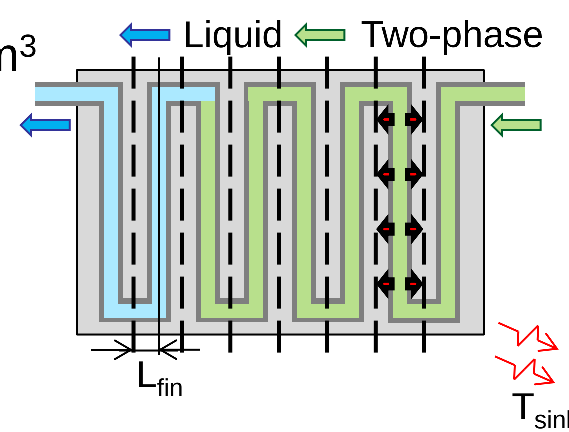
M	Mass [kg]
W	Power [W]
ΔP	Pressure drop [Pa]
$\dot{m}$	Mass flow rate [kg/s]
ρ	Density [kg/m^3]
η	Efficiency of pump [-]
δ	Thickness [m]
P	Pressure [Pa]
D	Diameter [m]
S	Allowable stress [Pa]
V	Volume [kg/m^3]

Not including the mass of evaporator and radiator which is made with panel of structure

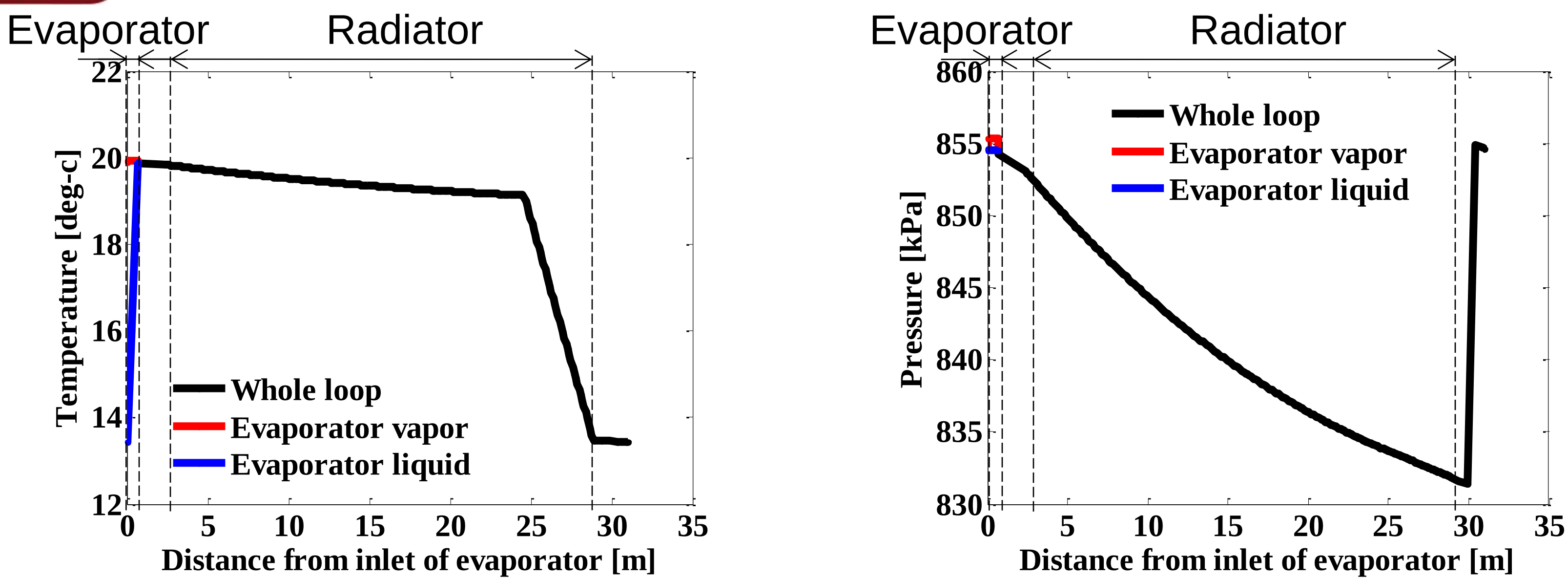
System analysis

- Inputs
  - Fluid : Ammonia
  - Mass Flow rate : 0.003kg/s
  - Whole loop
    - Thermal transporting length : 1.7m
    - Inner diameter of pipe : 3.87mm
    - Outer diameter of pipe : 6.35mm
  - Evaporator
    - Heat load : 500W
    - Temperature of surface : 20°C
    - Area : 0.5m^2
    - Wick pore diameter : 60μm
    - Pillar : 7.87 × 7.87 × 5.08mm^3
  - Radiator
    - Sink temperature : 4K
    - Length of fin : 25.4mm
    - Thickness of fin : 1mm
  - Pump
    - Net Positive Suction Head : 138kPa

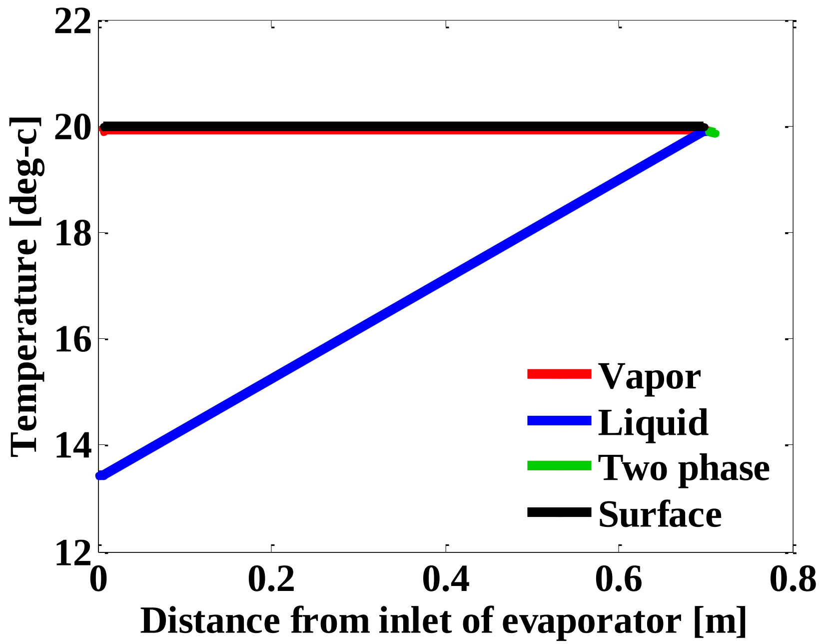


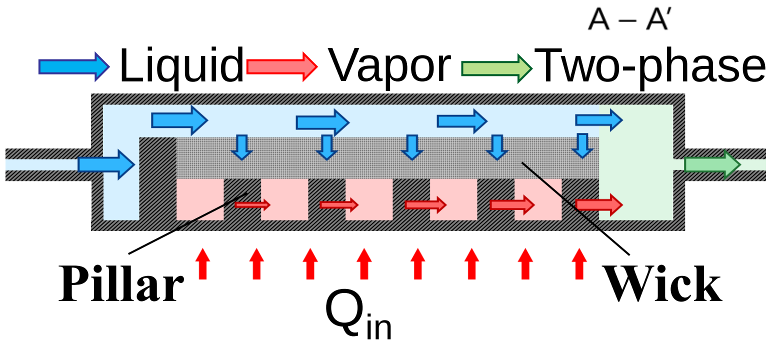


Results : Whole loop



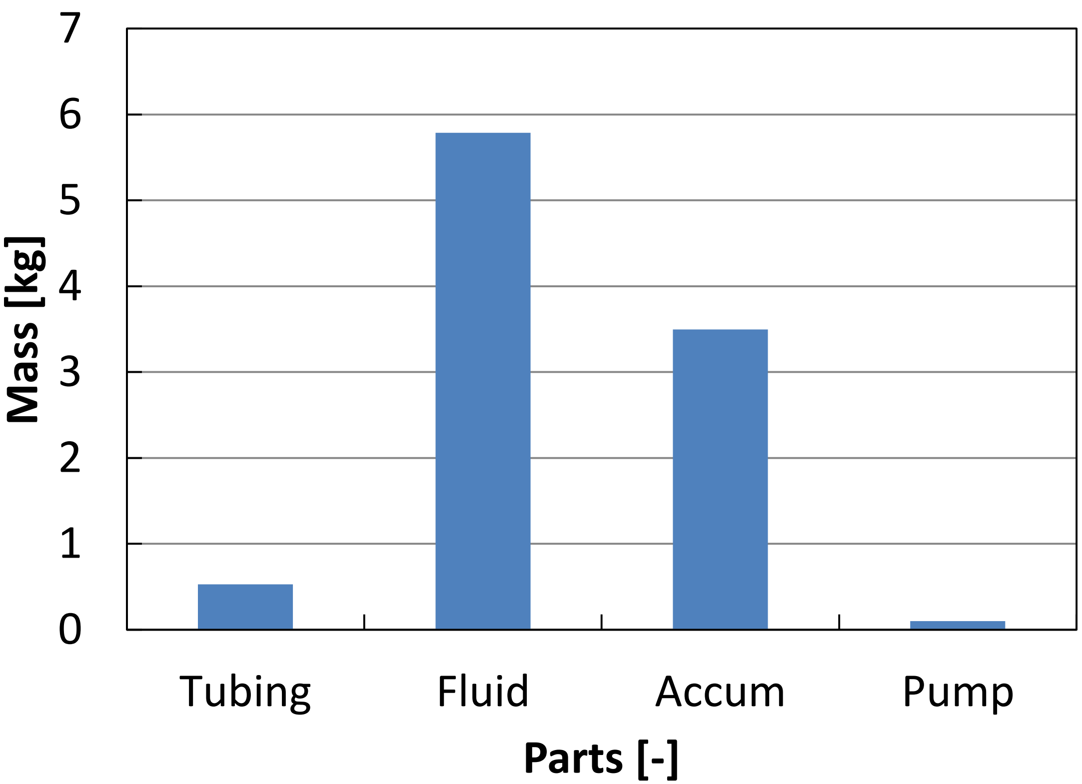
- Radiator length → Mass of Tubing, Fluids
- Absolute pressure → Mass of Accumulator
- Pressure drop → Mass of Pump





- Liquid is heated from subcooled to saturation
- Spatial temperature of surface fulfills the requirement $< 3^{o}C$

Results : System mass



- Total Mass is 9.96 kg
- Mass of fluid is the largest

Evaluating the working fluid

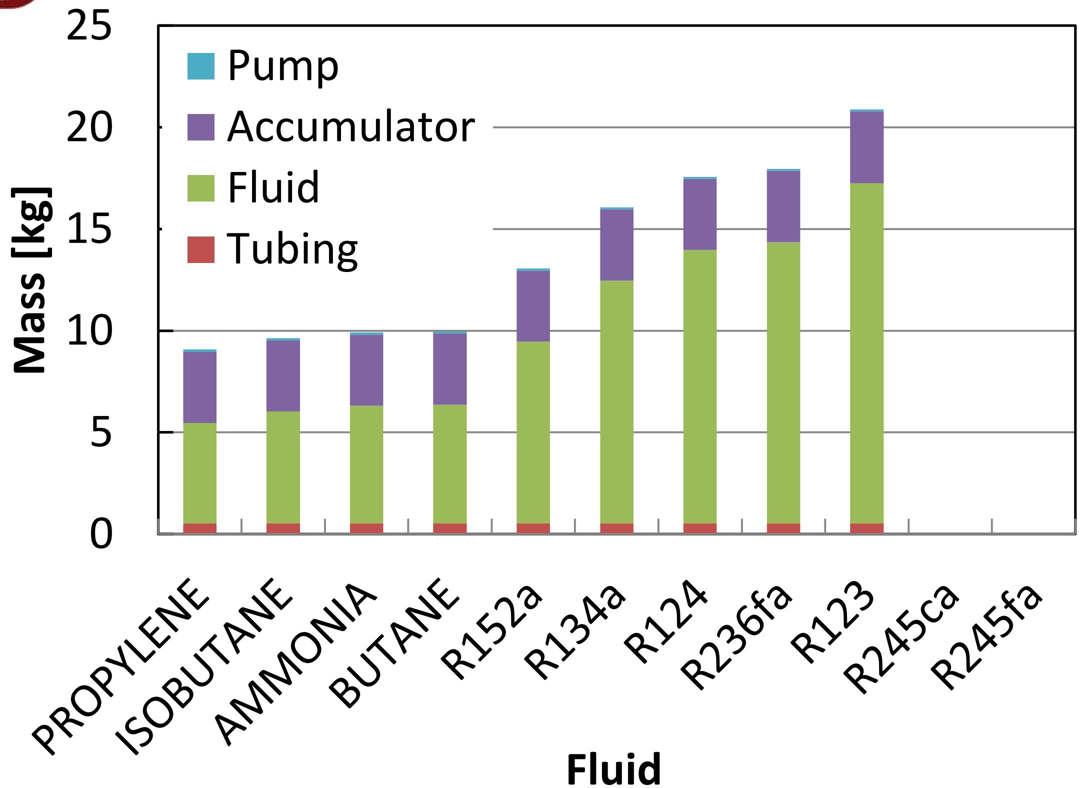
Working fluid selection

- Criteria
  - Saturation pressure < 1.4 MPa at 20 ^{o}C
  - Freezing point < -70 ^{o}C
  - Availability
- Working fluids
  - AMMONIA
  - R12
  - R134A
  - R152A
  - R124
  - ISOBUTANE
  - R142B
  - C318
  - R236FA
  - BUTANE
  - R245FA
  - R245CA
  - R114
  - R11
  - R123
  - R141B
  - R113
  - PROPYLENE
  - WATER

Criteria

  - AMMONIA
  - R134A
  - R152A
  - R124
  - ISOBUTANE
  - R236FA
  - BUTANE
  - R245FA
  - R245CA
  - PROPYLENE
  - R123

Result : System mass



Name	Density [kg/m^3] (at 20 ^{o}C)
PROPYLENE	515.02
ISOBUTANE	557.04
AMMONIA	610.42
BUTANE	578.76
R152A	912.34
R134A	1225.9
R124	1372.9
R236FA	1377.2
R123	1477.0

- Fluids occupy the mass of system
- Density of working fluid is critical for mass of system
- Propylene, Isobutane, Ammonia and Butane fulfil the requirement of mass < 10kg

Conclusion

- Evaluating the working fluids by total mass of system with 1D steady model of 2PMPFL
  - 1D steady 2PMPFL model for mass of system is developed
  - System analysis has been done.
  - Evaluating the working fluid
    - Working fluid drives the mass of system with the assumed evaporator design.
      - Density of working fluid is the key factor of mass of system
    - Propylene, Ammonia, Isobutane and butane fulfil the requirement of mass < 10kg

Acknowledgement

We are grateful to Eric Sunada, Pradeep Bhandari, Benjamin Furst and Stefano Cappucci.

This study was supported by IFS Graduate Student Overseas Presentation Award.